* Chapter 8 Sediment Measurement Techniques

Section I
Sediment Measurement Equipment

8-1. General

Satisfactory resolution of problems associated with sediment transported in streams requires both an understanding of sedimentation processes and a knowledge base of physical data. Between 1925 and 1940, in order to gather data for an increasing number of sediment studies, investigators developed new sediment samplers to measure fluvial sediment. However, developmental efforts were independent from one another, and most of the samplers were placed into service without calibration. As a result, a reliable database was not being obtained because the data were not comparable nor could their accuracy be evaluated. In 1939, the United States Government organized an Interagency program to study methods and equipment used in measuring sediment discharge and to improve and standardize equipment and methods. This organization is known as the Federal Interagency Sedimentation Project (FISP).

8-2. Federal Interagency Sedimentation Project

FISP was initially located at the Institute of Hydraulic Research at the University of Iowa. In 1948, it was moved to the St. Anthony Falls Hydraulic Laboratory, at the University of Minnesota. In 1992, it was relocated to the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. The Corps of Engineers has always been a major contributor to FISP and has benefitted greatly both from the use of the standardized equipment and procedures developed by the project, and from the reliable database generated by other agencies. Each Federal agency that provides financial support to FISP has one member on a technical subcommittee which guides the work of the project.

8-3. Characteristics of Ideal Sediment Sampler

The requirements of an ideal time-integrating suspended sediment sampler were summarized by Nelson and Benedict (1951).

a. The velocity at the entrance of the intake tube should be equal to the local stream velocity.

b. The intake should be pointed into the approaching flow and should protrude upstream from the zone of disturbance caused by the presence of the sampler.

c. The sample container should be removable and suitable for transportation to the laboratory without loss or spoilage of the contents.

Furthermore, the sampler should

d. Fill smoothly without sudden inrush or gulping.

e. Permit sampling close to the streambed.

f. Be streamlined and of sufficient weight to avoid excessive downstream drift.

g. Be rugged and simply constructed to minimize the need for repairs in the field.

h. Be as inexpensive as possible, and consistent with good design and performance.

The 35 samplers developed and used prior to 1940 were tested by FISP, and the results indicated that none met the criteria stated above.

8-4. Standardized Equipment

The US-series of suspended-sediment samplers developed by FISP embody most of the required and desirable features for an ideal sampler. All US-series integrating samplers provided by FISP are designed and calibrated to sample isokinetically. That is, the water-sediment mixture moves with no acceleration from the ambient flow into the sampler's nozzle intake. This ioskinetic property is critical to obtaining an accurate representation of sediment concentration. The samplers developed by FISP are designated based on their function and the year designed. For example, with a US DH-75 sampler, D signifies depth integrating, H signifies hand held, and 75 indicates the sampler was designed in 1975. A US P-61 is a point (P) integrating sampler designed in 1961. Except in unique circumstances, when specialized equipment is required, standardized equipment, provided and calibrated by FISP, should be used for data collection for Corps of Engineers projects. Inquiries regarding performance specifications and purchase of these samplers should be addressed to the Federal Inter-Agency Sedimentation Project, CEWES-HR-RF, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. *

*
8-5. Depth-Integrating Samplers

Depth-integrating samplers are designed to accumulate a water-sediment sample as the instrument is lowered to the streambed and raised to the surface at a uniform rate. The nozzle, either 1/8, 3/16, 1/4, or 5/16 in. in diameter, is always open. Use of the 1/8-in. nozzle is discouraged because it tends to plug easily and surface roughness in the bore may affect the sampling rate. This nozzle is generally used only when conditions do not permit use of larger nozzles. Particle sizes which can be collected range from clays through sands. The sampling depth is limited to about 15 ft or less depending on the size of the nozzle.

a. Hand-held. Where streams can be waded or where a low bridge is available, lightweight hand-held samplers can be used to obtain depth-integrated suspended-sediment samples. The US DH-48 is a streamlined aluminum sampler, which weighs 4.5 lb, collects samples in a pint bottle, and can sample to within 3.5 in. of the bed. The US DH-59 and US DH-76 are bronze cast samplers, collect samples in pint and quart size bottles, respectively, and were designed to be suspended from a hand-held rope in streams too deep to wade. The US DH-59 and US DH-76 weigh about 22 and 25 lb, respectively; applicability is limited to cases where the velocity is less than 5 fps. These lightweight hand-held samplers are the most commonly used for sediment sampling during normal flow in small and intermediate sized streams. The US DH-75 was designed for use in subfreezing winter conditions. It is lightweight and therefore can be thawed easily with a small torch. The US DH-75 sampler may be used with a pint or a quart plastic bottle and most of the working parts are made of plastic.

b. Cable and reel. When streams cannot be waded, but are less than 15 ft deep, a US D-74 depth-integrating sampler can be used. The US D-74 is a 62-lb bronze cast sampler and is used with a cable and reel suspension. Samples are collected in a pint or quart bottle and the US D-74 can sample to within 4 in. of the streambed. Maximum calibrated velocity for the US D-74 is 6.6 fps. The US D-77 was designed to collect large-volume (3 ℓ) depth-integrated samples. This sampler is used extensively in water-quality sampling because all components that contact the sample are made of plastic or Teflon. The US D-77 weighs 75 lb and samples to within 7 in. of the bottom. Maximum calibrated velocity is 8 fps.

8-6. Point-Integrating Samplers

Point-integrating samplers are more versatile than the simpler depth-integrating types. They can be used to collect a sample at any selected point in the water column, or they can be used to sample continuously over a range of up to 30 ft in depth. This limit results from the requirement to maintain ambient pressure in the sample bottle as the sample is collected. Because of their greater mass, point-integrating samplers can be used in streams too deep or swift for the standard depth-integrating samplers. Point-integrating samplers contain an air compression chamber which allows for pressure equalization in the sample bottle up to depths of 180 ft when a pint-sized sample bottle is used. With a quart-sized bottle, depths up to 120 ft can be sampled. Sampling is controlled by a rotary valve, which is operated electrically by the operator. By positioning the sampler at the streambed before opening the valve, and sampling while transiting upward to the surface, a depth-integrated sample can be collected through a 30-ft deep water column. In deeper streams, a depth-integrated sample can be collected by partitioning the total depth into segments, up to about 30 ft each, and by using a constant transit velocity throughout. The US P-61, which weighs 105 lb, is the classical point-integrating sampler. The distance between the nozzle and the sampler bottom is 4.3 in. A lightweight version of the US P-61 is the aluminum cast US P-72, which weighs about 41 lb. For swifter streams, the 200-lb US P-63 can be used. The US P-63 can sample to within 5.9 in. of the streambed. The US P-50, weighing 300 lb, is a special point-integrating sampler developed for and used on large rivers such as the lower Mississippi.

8-7. Auxiliary or Automatic Sampling Equipment

Single-stage samplers were developed as an aid in obtaining information on flashy streams. The most severe limitation of single-stage samplers is that they collect samples of the water-sediment mixture at a fixed point in the steam and, therefore, are most effective in streams carrying predominately fine sediments. The single-stage sampler may be a static sampler such as the US U-59, which consists of a pint bottle filled from a vertical or horizontal intake tube using siphonic action or it may utilize a pump. In case of the pump, the velocity in the intake is not usually equal to the stream velocity, and the intake does not usually point into the flow. Whereas, silt and clay
*

* sizes collected in such samplers may be representative, pumping samplers generally significantly underestimate the concentration of sand sizes in the flow field (Hall and Fagerburg 1991) as shown in Figure 8-1. Sediment samples collected from automatic sampling equipment must be calibrated to samples collected from cross-section depth-integrated or point-integrated samples for reliable results.

8-8. Bed Samplers

a. FISP samplers. Bed samplers designed by FISP are limited to collecting samples where the maximum grain size is less than fine gravel. The samplers are also limited to relatively firm beds; i.e. they are not designed to collect samples from unconsolidated deposits of silt or clay. The US BMH-53 is a hand-held piston-type sampler for sampling the bed of wadable streams. The collecting end of the sampler is a stainless steel thin-walled cylinder 2 in. in diameter and 8 in. long. Sediments composed primarily of sands are difficult to sample with the US BMH-53 because the material tends to fall from the barrel when the cutting edge is lifted above the streambed. For noncohesive materials, in wadable streams, the US RBM-80 sampler is available. It is a manually operated lever-and-cable system with a rotating bucket that collects a sample along a 51-mm arc. The bucket closure is sufficiently sealed to prevent loss of the sample while the instrument is lifted through the water column. The bed of deeper streams or lakes can be sampled with the US BMH-60. This is a hand-line streamlined sampler with a spring-driven rotary bucket. It weighs 32 lb and is easiest to use in any reasonable depth when stream velocities are under 3 fps. The rotary bucket penetrates the bed to about 1.7 in. and holds about 175 cc of sample. The US BM-54 is a cable and reel suspension sampler with a design similar to the US BMH-60, but weighing 100 lb. The extra weight allows for sampling at any reasonable depth and in swifter streams.

b. Nonstandard bed samplers. Nonstandardized bed samplers are frequently used for special applications,

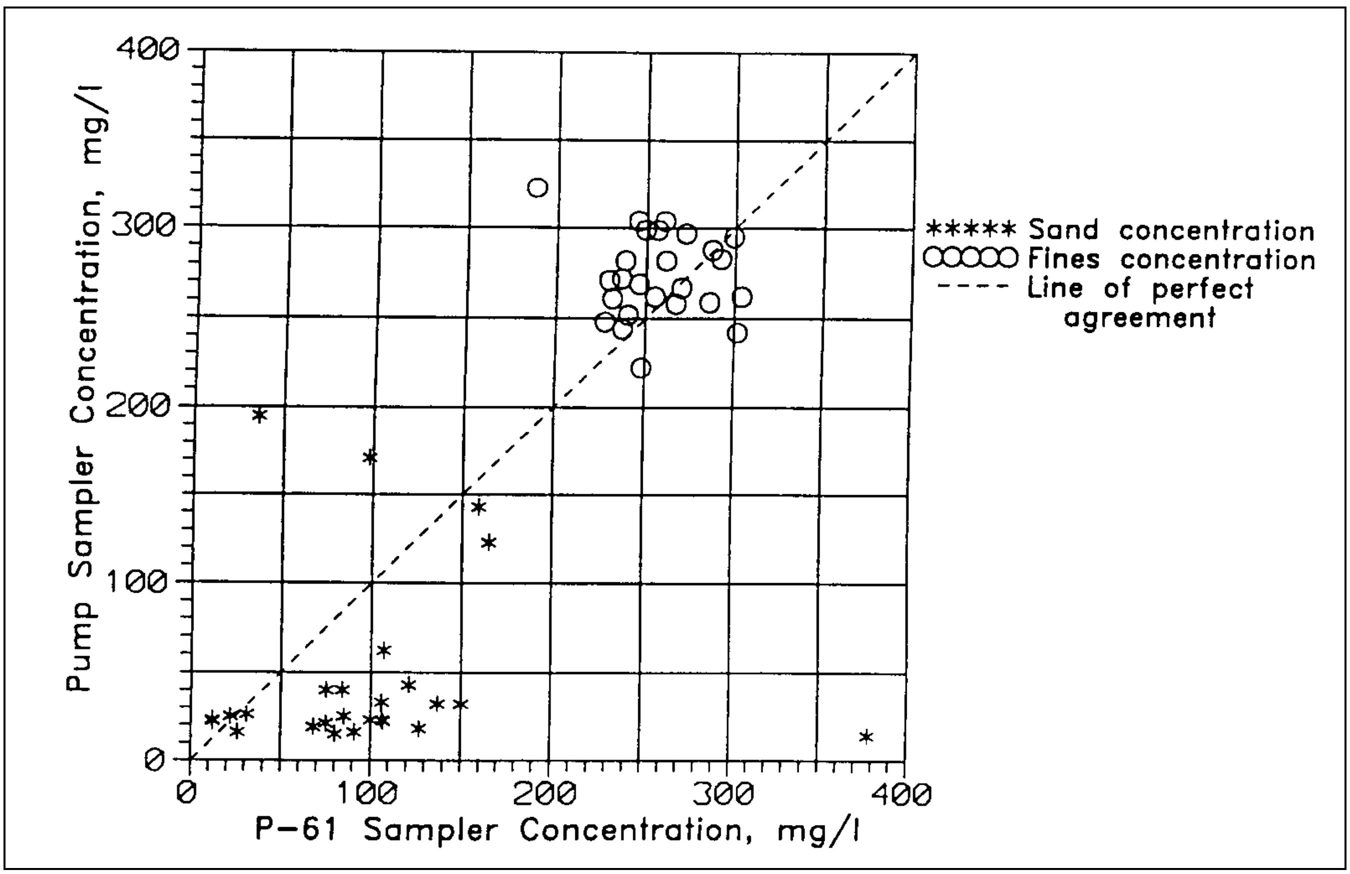

Figure 8-1. Comparison of sediment load measured with pump and US P-61 samplers

*

* or when the standardized equipment is deemed unnecessary. Drag bucket, pipe samplers, and scoop samplers simply collect a sample into an open container by dragging or scooping. The disadvantage with these sampler types is that material, especially fine material, may be washed out of the container as the sample is brought to the surface. Clamshell samplers can be used when stream velocity is low. These have the disadvantage of frequent nonclosure if gravel is present in the sample, and they create a significant disturbance on the bed of streams with moderate to high velocity.

c. Gravel-bed samplers. Samplers for obtaining short cores in shallow water in gravel- or cobble-bed streams are described in ASTM Standard D-4823 (ASTM, published annually). These include a barrel sampler, with a serrated cutting edge, that is driven into the bed. Once the sampler is in place, sediment is excavated, by hand, layer-by-layer. Another sampler is a freeze-core sampler. This device is a hollow probe that is driven into the streambed and cooled with liquid nitrogen. The device is then extracted with a frozen core of sediment adhered to it.

d. Core samplers. When the purpose of the sampling program is to obtain information on the vertical composition of deposits to determine density and compaction, then an undisturbed sample is required. These samples are collected using core samplers or piston-core samplers that have removable sample-container liners. Fine sediments are generally cored easily, but in sand and gravel deposits it is difficult to obtain deep cores. Coring deep into sediment generally requires drilling equipment or special pile-driving equipment, which may produce samples that are highly disturbed or compacted. Several deep-core samplers are described in ASTM Standard D-4823 (published annually), and ***Sedimentation Engineering*** (ASCE 1975, pp 357-369.)

e. Acoustical techniques. Recent advances in geoacoustics have resulted in the development of geophysical methods to assess the characteristics of bottom and subbottom sediments. Specifically, the engineering properties of sediments (i.e. density, mean grain size, soil classification, etc.) have been empirically related to the measured acoustic impedance of different sediment types. Acoustic impedance, z, is the product of the mass density, ρ, and elastic compressional wave sound velocity, v, ($z = \rho v$) through a sediment layer and, thus, represents the influence of the medium's characteristics on reflected and transmitted acoustic waves. McGee et al. (1995) present a detailed discussion of the application of acoustical techniques for the assessment of in situ sediment properties.

8-9. Bed-Load Samplers

Bed load is difficult to measure for several reasons. Any mechanical device placed on the bed disturbs the flow and hence the rate of bed-load movement. In addition, bed load is characterized by extensive spatial and temporal variability. For this reason, the sampling technique is just as important as the sampling equipment. The Helly-Smith bed-load sampler is the most commonly used sampler in the United States. FISP recommends a bed-load sampler with a nozzle flare angle that is different from that on the Helly-Smith sampler. In general, the overall sampling efficiency of a specific sampler is not constant, but varies with size distributions, stream velocities near the bed, turbulence, rate of bed-load transport, and the degree of filling of the sampler.

Section II
Standard Sampling Procedures

8-10. General

Detailed procedures used by the U.S. Geological Survey for measurement of fluvial sediments are contained in a report by Edwards and Glysson (1988) (which may be obtained from the Distribution Branch, U.S. Geological Survey, 604 So. Pickett Street, Alexandria, VA 22304) and in ASTM Standard D-4411 (published annually). A brief summary of these procedures is outlined herein.

8-11. Depth Integration

The procedure for collecting depth-integrated samples is to lower the sampler to the water surface, so that the nozzle is out of the water and the tail vane is in the water until the sampler is properly aligned with the flow. Depth integration is achieved by lowering the sampler to the streambed at a uniform transit rate and then immediately raising the sampler at a uniform rate until the nozzle clears the water surface. Each transit must be at a uniform rate, but the raising and lowering transits may be at different rates. In order to minimize the effect of non-horizontal flow entering the nozzle, transit rates should not exceed four-tenths of the mean velocity. Other factors may limit the transit rate to significantly lower values. Transit depths are limited by the rate of air compression in the sample bottle. In addition, transit rates should be such that at the end of sampling, the sample *

* bottle is about two-thirds full. If the bottle is overfilled, i.e. filled to within 1.5 in. of the top, the sample should be discarded. Graphs for determining transit rates as a function of nozzle diameter, mean velocity, and depth of integration are provided in Edwards and Glysson (1988, pp 69-72). When the stream is shallow, or the velocity is low, several transits may be made to obtain the appropriate sample volume and several sample verticals may be included in a single sample bottle.

a. Single vertical. Streams with a stable cross section and insignificant lateral variation in the suspended-sediment load may be sampled using a single vertical. The same vertical is usually used for all discharges. The best location for the single vertical is determined by trial when the station is established. Detailed sediment-discharge measurements employing several verticals across the entire width of the stream at a range of discharges must be conducted at a new gaging site in order to determine the location for the single vertical sampling point. The vertical should be located at least 10 ft from any supporting pier. The results of the fixed vertical should be compared with frequent cross-sectional sampling in order to verify an adjustment factor for the total sediment concentration. This adjustment factor should especially be checked after major flood flows that alter the channel shape.

b. Multiple verticals. Lateral variation in depth, velocity, roughness, and grain size may make it unrealistic to relate sediment concentration for the entire cross section to concentration at a single vertical. A realistic sampling program may require sampling at two to five or more verticals. Verticals may be located by one of two methods: the method of the centroids-of-equal-discharge increments (EDI) across the stream, where the channel cross-sectional area is divided laterally into a series of subsections, each of which conveys the same water discharge; or the method of equally spaced verticals across the stream and an equal-width-increment (EWI) at all verticals (sometimes referred to as equal-transit-rate: ETR). The EDI method is usually limited to streams with stable channels where discharge ratings change very little during a year. The EWI method is most often used in shallow and/or sand-bed streams where lateral flow distribution is unstable. On the order of 20 verticals are usually ample for the EWI method. A nomograph to determine the number of sampling verticals required to obtain results within an acceptable relative standard error based on the percentage of sand in the sample, the average velocity, and the depth is given in Edwards and Glysson (1988, p 68). The EDI method requires some knowledge of the streamflow distribution before the sampling verticals can be selected, but this method can save time and labor over the EWI method, especially on larger streams because fewer verticals are required. Samples collected using the EDI method may be composited to obtain total concentration if sample bottles contain equal, or nearly equal, quantities of sample. Samples collected using the EWI method can be composited regardless of the volume in each sample.

c. Point integration. Point-integrating samplers are used in streams where depth exceeds the recommended 15 ft for a depth-integrating sampler and where the combination of depth and velocity cause the sample bottle to overfill at the maximum allowable transit rate. Also, in high velocities, the lighter depth-integrating samplers are unstable and the more massive point-integrating samplers should be used. Both the EWI and EDI methods are applicable to point-integrating samplers when they are used for depth integration. Stream depth increments up to 30 ft can be measured with point-integrating samplers by integrating the depth in only one direction. When depth integration is used in only one direction, at least two samples should be taken and composited at each vertical: one by downward integration and one by upward integration. Point-integrating samplers are sometimes used to obtain sample concentrations at several points or levels in the vertical from which the distribution of sediment concentration in the vertical can be computed. This method is slower and more labor-intensive than depth integration and should be reserved for special studies.

8-12. Bed-Load Sampling

Bed load moves sporadically as a series of pulses and also varies laterally across the stream. Due to the significant temporal and spatial variation in bed-load transport, many repetitive measurements must be made at a number of different lateral locations. Initially, 10 to 20 sampling verticals should be used. The sampling sequence must be long enough to include the passage of several bed forms to account for the temporal variation in transport rate. Consideration must be given to the variation in hydraulic forces through a reach that may cause certain size classes to move primarily as bed load in one reach, but as suspended load in another reach. This extensive sampling needs to be made over the entire range of stream discharges in order to obtain a reliable bed-load transport rating curve. The suggested technique for bed-load sampling is to sample at 20 verticals initially to define the active bed-load transport zone, then sample at 10 or more verticals *

* within that zone on subsequent transects. At least four transects should be taken. If it is apparent that temporal variations are more significant than spatial variations, then a smaller number of verticals may be sampled (about five), but many replications at each vertical should be conducted.

8-13. Bed Sampling

a. General. Deposited sediment is sampled to provide information on such things as size, specific gravity, shape, and mineralogy of the particles that make up the bed; stratigraphy, density, and compaction of the deposits; and the quantity and distribution of contaminants. For some of these purposes a sample can be disturbed; others require undisturbed sampling. Different samplers and sampling procedures are available for different environments.

b. For sediment transport studies. Typically, streambed samples are obtained in order to determine the potential for sediment transport. For this purpose, undisturbed samples are not required. The sample is taken from the upper 2 in. of the bed surface in sand-bed streams. In gravel-bed streams, samples of the armor layer and the subsurface layers should be collected. The sample depth for the armor layer should be about equal to the diameter of the maximum size class in the bed. The depth and quantity of sample for the subsurface depends on the size of sediment and the equipment being used. When sampling for sediment transport studies, do not sample over long distances along the stream. Collect all samples along cross sections to characterize that reach. Then proceed to the next sampling cross section and repeat the procedure.

c. Samples from dry beds. Sampling in the dry is preferred because there is less opportunity for fine-size classes to be lost from the sample during collection. Samples from dry beds are typically collected with a shovel or scoop. If there is an obvious layer of fine material on the surface of a dry bed, this should be removed before the sample is taken.

d. Samples from streams with flowing water. In order to obtain satisfactory samples in flowing water, the bed sampler should enclose a volume of the bed material and then isolate the sample from the water currents while the sampler is being lifted to the surface. The sampler should disturb the flow field as little as possible while taking a sample. These criteria are met with standardized FISP US BM-54 and US BMH-60 samplers. Under certain flow conditions, simple drag bucket and pipe samplers have been shown to produce bed gradations similar to those obtained with the US BM-54. A comparison with standardized samplers should be conducted for each case. Open-ended drag bucket and pipe samplers are typically used from a boat. One technique is to lower the sampler to the bed and allow the boat to drift with the current. The sample is dredged up as the boat moves downstream. As the boat continues to drift, the sampler is hoisted back to the surface.

e. Streams with coarse surface layers. Streams with coarse surface layers present a particular problem. For numerical studies of nonequilibrium flow conditions, the sample should include the coarse surface layer so that all of the particle sizes available for armoring are included in the sample. This practice requires that the coarse surface layer comprises only a small fraction (less than 5 percent) of the total sample. It is frequently necessary to obtain separate gradations of both the coarse surface layer and the subsurface layer.

f. Lateral variations. Lateral variation in the bed gradation is significant, especially in sand-and-gravel bed streams and at channel bends. At least three samples should be taken across the cross section to account for lateral variations. In streams with variable depths more samples are required. Taking bed samples at crossings where flow distribution is typically more uniform, reduces the lateral variation in the samples. However, at low flow, crossings may become coarser than the average gradation and should not be selected as a sampling location for sediment transport studies. This is especially true of steep streams that develop riffle and pool planforms. Samples collected on point bars or alternate bars may exhibit considerable variation. Figure 8-2 illustrates a typical bed gradation pattern on a point bar. Note that, although the typical grain sizes found on the bar surface form a pattern from coarse to fine, there is no one location which always captures the precise distribution which will represent the entire range of processes in the prototype. There is no simple rule for locating sampling sites. The general rule is "always seek representative samples." That is -- ***carefully select sampling locations and avoid anomalies which would bias either the calculated sediment discharge or the calculated bed stability against erosion.*** A good practice is to take samples at a crossing and at a point or alternate bar just above the low water level to establish a range of uncertainty for the bed gradation. Dead water areas behind sandbars or bridges should be avoided. *

*

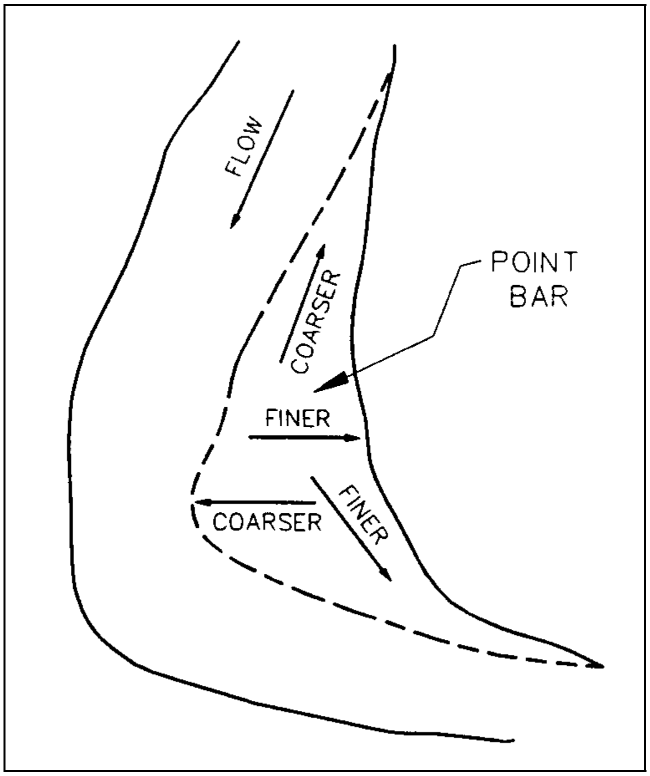

Figure 8-2. Gradation pattern on a bar

g. Coarse beds. When bed particle size is too large to obtain a manageable quantity of sample for sieve analysis, a pebble count (Wolman 1954) may be conducted where individual particles are collected at random by hand and the intermediate (b) axis is measured. This method requires that the stream be wadable. At least 100 particles should be included in the sample. One method for choosing the particles is a random walk laterally across the stream or longitudinally along a point bar, another is to set up a grid and measure particles at the intersection of grid points. The gradation curve developed from these data is based on the number of particles in each size class, not their weights.

8-14. Suspended-Sediment Sampling in Lakes, Reservoirs, and Estuaries.

Sediment measurement in low-velocity environments requires different equipment and techniques than in streams. As flow velocity approaches zero, movement, if any, results from complex circulation patterns, density currents, or tidal flow. Cross-sectional areas are usually very large; and instantaneous water discharges are rarely known. Sampling techniques need to be evaluated for accuracy and pertinence to the objective of the sampling program. Most samplers used in low-velocity environments are point or trap samplers that are oriented vertically and do not sample isokinetically. Frequently, samples are collected using pumping samplers. Due to continuous changes in sediment concentration in estuaries, neither the EDI or EWI methods for sampling are appropriate. General practice is to sample continuously through a tidal cycle at a number of locations to define temporal variation at each location. Field procedures for lake and reservoir sampling are found in ***Sedimentation Engineering*** (ASCE 1975, pp 369-375.) Procedures for estuarine sampling are found in EM 1110-2-1607.

Section III
Laboratory Analysis

8-15. Suspended-Sediment Concentration

Evaporation and filtration are the two most frequently used methods for determining sediment concentration. The filtration method is faster if the quantity of sediment in the sample is small and/or relatively coarse grained. In addition, if the quantity of sediment is small, the evaporation method requires a correction if the dissolved-solids concentration is high. The evaporation method is usually best for high concentrations of sediment (>2,000 mg/l), such as those encountered in many arid-region streams. Laboratory procedures for both methods are well documented (ASCE 1975, pp 404-406; Guy 1969; U.S. Interagency Report 1941).

8-16. Particle-Size Analysis

Sediment particles vary not only in size, but in shape and specific gravity. Particles of a given size will behave as if they were larger or smaller depending on how their shape and specific gravity compare with standard values. Due to the wide range in sediment characteristics, particle size should be defined in terms of the method of analysis used to determine the size. Methods for determining sediment gradations are grouped into fine-sediment methods and coarse-sediment methods. The most commonly used methods for determining the gradation of fine sediment are the hydrometer, the bottom withdrawal tube, and the pipet. The X-ray method is a new method for determining fine sediment gradation. Two generally accepted methods for determining the size-distribution of sand are the sieve and visual-accumulation tube methods. The sieve method measures physical diameter, whereas all other methods measure sedimentation diameter. A given
*

* sediment sample may require more than one method of analysis because of the broad range of particle sizes. Recommended quantities of sediment sample, the desirable range in concentration, and the recommended particle size range for the most frequently used methods of particle-size analysis are shown in Table 8-1. Additional guidance for selection of a particle-size analysis is given in ASTM Standard D-4822 (published annually).

Many suspended-sediment samples will not contain sufficient sediment for any of these methods, in which case, the analysis may be limited to simply determining the percentage of sands and fines. A greater quantity of sediment may be obtained by using larger bottles in samplers or by compositing samples. Sometimes samples require splitting to obtain a reasonable quantity for analysis.

a. Hydrometer method. Laboratory procedures for conduction of the hydrometer method are contained in *EM 1110-2-1906.* This method has been used extensively in the study of soils. Although the method is relatively simple and inexpensive, its use in sediment work has been limited to fine-grained bed and bank material because of the need for a relatively large quantity of sediment.

b. Bottom withdrawal method. The bottom-withdrawal method requires specially constructed and calibrated tubes. It is not used extensively. This method is more accurate for very low concentrations of fine materials than the pipet method; however, it is more time consuming. The bottom withdrawal method is described in ***Sedimentation Engineering*** (ASCE 1975, pp 418-424)

c. Pipet method. The pipet method is the most routinely used method for fine sediment (clay and silt) analysis. The sample initially is dispersed uniformly throughout the pipet apparatus. Concentrations of the quiescent suspension are determined at predetermined depths and times based on Stokes law. The primary disadvantage with this method is its high labor intensity. The pipet method in described in ***Sedimentation Engineering*** (ASCE 1975, pp 416-418), and Guy 1969).

d. X-ray methods. The U.S. Geological Survey has recently approved usage of X-ray grain-size analyzers to determine fall diameter for clay and silt mixtures. The sample is dispersed uniformly in the instrument which measures decreasing concentration with time. Cumulative mass percentage distributions are determined automatically. X-ray analysis requires less time than the pipet method and is therefore less expensive. Comparisons of pipet and X-ray methods have shown that X-ray methods tend to produce slightly finer gradations. When the X-ray method is employed, duplicate samples on at least 10 percent of the samples at a site should be taken until a relationship between the X-ray and pipet results can be established.

e. Sieve method. Sieve analysis is a relatively simple method for obtaining a gradation for sediment larger than 0.0625 mm. Unfortunately, U.S. standard sieves do not correlate exactly with the AGU size class classification system. A set of U.S. standard sieves range between 3 in. and 0.074 mm. As discussed in Chapter 7 sediment diameters determined from sieve analysis do not necessarily correspond to equivalent spherical diameters. Sieve analysis does not account for variations in particle shape or specific gravity. Procedures for application of sieve analyses are found in *EM 1110-2-1906.* The required sample size is a function of the maximum particle size. A guide for obtaining a minimum-weight sample is given in Table 8-2.

Table 8-1
Recommended Quantities for Particle-Size Analysis

Method	Size Range, mm	Analysis Concentration, mg/l	Quantity of Sediment, grams
Sieve	0.062 - 64		0.07 - 64,000
VA tube	0.062 - 2.0		0.05 - 15.0
Pipet	0.002 - 0.062	2,000 - 5,000	1.0 - 5.0
BW tube	0.002 - 0.062	1,000 - 3,000	0.5 - 1.8
Hydrometer	0.002 - 0.062	40,000	30.0 - 50.0

*

*

Table 8-2
Sample Size for Sieve Analysis

Maximum Particle Size, in.	Minimum Weight of Sample grams	pounds
3.0	64,000	140
2.0	19,000	42
1.5	8,000	18
1.0	2,400	5.3
0.75	1,000	2.2
0.5	300	0.66
0.375	150	0.33
0.187	50	0.11
Particle Size Range, mm		
16.0 - 1.0	20	0.044
2.0 - 0.25	0.5	0.0011
0.5 - 0.062	0.07	0.00015

Note: For streams with maximum sizes larger than 3 in., the required sample weight should be at least 100 times the weight of the maximum size.

f. Visual accumulation method. The visual accumulation (VA) method is used to determine the fall diameter of sands. Sediment finer than 0.062 mm is removed from the sample and analyzed by either the pipet or bottom withdrawal methods. Particles larger than 2 mm must be removed and measured by sieve analysis. In the VA method, sediment is added at the top of a settling tube and the deposited sediment is stratified according to the settling velocities of the various particles in the mixture. A continuous trace of the deposited sediment at the bottom of the VA tube is produced by the analysis. The VA apparatus may be obtained from the FISP which also supplies an operator's manual.

Section IV
Developing a Sediment Discharge Rating Curve

8-17. Preparation from Measured Data

Success in developing sediment-discharge rating curves will depend on the foresight in establishing an adequate sediment measuring program prior to the need for data. Sediment-discharge rating curves are prepared from measured data, sometimes available in annual USGS Water Resource Publications for each state. Calculated mean daily sediment discharges are frequently published; these are calculated values and should not be used to develop a sediment-discharge rating curve. An example data set is shown in Figure 8-3. Note that fall diameters are reported in columns 7-14 and sieve diameters in columns 15-20. Sieve analyses were apparently conducted for samples with low sediment concentrations, where there were insufficient quantities available for VA analyses. For most of these samples, only a fines/sand break was determined.

a. Separation by sediment load type. Sediment-discharge rating curves should be prepared for the total measured load and the measured bed-material load. The sediment-discharge rating curve for the total measured suspended load can be developed from data in columns 3 and 6 in Figure 8-3 (although a much larger data set is required for a reliable rating curve). Total suspended sediment load alone is not sufficient to analyze the sediment discharge characteristics. It is also important to separate the wash load from the bed-material load because their transport is governed by different relationships: wash load is dependent on upstream supply, and bed-material load is dependent on the availability of the sediment in the streambed. The size-class break between wash load and bed-material load is frequently assumed to correspond to the break between sand and silt (0.0625 mm); however, this assumption is not always valid. Bed gradations at the gage site are required in order to distinguish the wash load from the

*

*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
DATE	TIME	STREAM-FLOW, INSTAN-TANEOUS (CFS) (00061)	TEMPER-ATURE (DEG C) (00010)	SEDI-MENT, SUS-PENDED (MG/L) (80154)	SEDI-MENT, DIS-CHARGE, SUS-PENDED (T/DAY) (80155)	SED. SUSP. FALL DIAM. % FINER THAN .002 MM (70337)	SED. SUSP. FALL DIAM. % FINER THAN .004 MM (70338)	SED. SUSP. FALL DIAM. % FINER THAN .016 MM (70340)	SED. SUSP. FALL DIAM. % FINER THAN .062 MM (70342)	SED. SUSP. FALL DIAM. % FINER THAN .125 MM (70343)	SED. SUSP. FALL DIAM. % FINER THAN .250 MM (70344)	SED. SUSP. FALL DIAM. % FINER THAN .500 MM (70345)	SED. SUSP. FALL DIAM. % FINER THAN 1.00 MM (70346)	SED. SUSP. SIEVE DIAM. % FINER THAN .062 MM (70331)	SED. SUSP. SIEVE DIAM. % FINER THAN .125 MM (70332)	SED. SUSP. SIEVE DIAM. % FINER THAN .250 MM (70333)	SED. SUSP. SIEVE DIAM. % FINER THAN .500 MM (70334)	SED. SUSP. SIEVE DIAM. % FINER THAN 1.00 MM (70335)	SED. SUSP. SIEVE DIAM. % FINER THAN 2.00 MM (70336)
NOV																			
01...	1000	577	7.5	152	237	--	--	--	--	--	--	--	--	57	72	84	95	100	--
08...	1415	799	12.5	223	481	--	--	--	--	--	--	--	--	40	51	75	98	100	--
29...	1145	940	9.0	578	1470	--	--	--	--	--	--	--	--	17	25	43	77	98	100
JAN																			
03...	1000	512	.0	277	383	--	--	--	--	--	--	--	--	19	31	62	93	97	100
FEB																			
01...	1230	791	6.0	38	81	--	--	--	--	--	--	--	--	72	81	96	99	100	--
28...	0900	1390	7.0	324	1220	--	--	--	47	55	82	100	--	--	--	--	--	--	--
APR																			
02...	0900	1460	8.0	411	1620	--	--	--	--	--	--	--	--	60	--	--	--	--	--
28...	1300	6440	12.0	2410	41900	7	8	11	28	45	70	96	100	--	--	--	--	--	--
MAY																			
02...	1200	4970	12.5	943	12700	--	--	--	36	59	84	98	100	--	--	--	--	--	--
JUN																			
01...	1200	5460	13.0	524	7720	--	--	--	43	57	73	97	100	--	--	--	--	--	--
13...	1600	6900	15.0	1490	27800	--	--	--	--	--	--	--	--	15	--	--	--	--	--
JUL																			
11...	1000	3550	22.0	299	2870	--	--	--	32	46	79	100	--	--	--	--	--	--	--
29...	0900	722	17.0	606	1180	--	--	--	--	--	--	--	--	96	--	--	--	--	--
AUG																			
15...	1015	304	23.5	234	192	--	--	--	--	--	--	--	--	93	95	98	100	--	--
SEP																			
12...	1430	409	26.0	273	301	--	--	--	--	--	--	--	--	94	95	99	100	--	--

Figure 8-3. Measured sediment-discharge data

*

* bed-material load. The bed gradation should account for lateral variations across the cross section using an appropriate averaging technique. Einstein (1950) recommended using only the coarsest 90 percent of the sampled bed gradation for computations of bed-material load. He reasoned that the finest 10 percent of sediment on the bed was either trapped material or a lag deposit and should not be included in bed-material load computations. Once the division between wash load and bed-material load is determined, the percent finer data from the appropriate column in Figure 8-3 can be used with the total concentration in column 5 and the discharge in column 3 to calculate wash load. If sufficient data are available, separate sediment-discharge rating curves should be developed for each size class in the bed-material load. For studies involving inflow to reservoirs, separate sediment-discharge rating curves should be developed for each size class in the wash load too. In order to accomplish this type of analysis it is necessary that adequate numbers of particle-size analyses are conducted on the collected sediment concentrations. Unfortunately, particle-size data are frequently insufficient to develop sediment-discharge rating curves as described in the preceding paragraph. In such cases, a minimum requirement is to develop separate curves for the fines (clays and silts) and the sands.

b. Approximations by calculation. When measured data are insufficient to develop a sediment-discharge rating curve for each size class, then sediment transport equations must be employed to develop rating curves for individual size classes. The percentage of each size class in the suspended load will vary with discharge (the percentage of fines will be greater at lower discharges). Therefore, it is inappropriate to develop sediment-discharge rating curves for mixed size-classes using the average of measured size-class fractions.

c. Adjustment for unmeasured load. Sediment-discharge rating curves developed from measured suspended-sediment data need to be adjusted to account for the unmeasured load. This can be accomplished using the Modified Einstein Equation (ASCE 1975, pp 214-220), if the hydraulic parameters, concentration data by particle size, and bed-material gradations are available. A computer program for computing the unmeasured load with the Modified Einstein Equation is available on the CORPS system (USAEWES). If data are not available, the unmeasured load may be assumed to be a percentage of the measured load equal to the percentage that the bed load is of the total load. Bed-load percentage for a stream can be determined using the Einstein or Toffaleti sediment transport equation. These are computerized in the CORPS system (USAEWES) and in SAM (Thomas, et al. 1995.)

d. Bed load. Developing sediment-discharge rating curves from measured bed-load data is more difficult. Bed load moves in pulses and varies laterally across the stream. Therefore, significantly more measurements are necessary to obtain a reliable average condition. It has been demonstrated in gravel-bed streams and flumes that the percentage of each size class in the bed load closely corresponds to its percentage in the subsurface layer (Andrews and Parker 1987; Kuhnle 1989; and Wilcox and McArdell 1993). If a given gravel-bed stream is in equilibrium, it is not unreasonable to assume that the percentage of each size class in the bed load equals the percentage in the bed substrate.

8-18. Scatter of Data Points

At most sediment gage sites a relatively good correlation between flow discharge and sediment discharge can be developed. However, sediment discharge depends on other variables as well, such as upstream supply, water temperature, roughness, and downstream stage. Therefore, data scatter is expected in sediment-discharge rating curves. At some gages, separate curves need to be developed for the rising and falling limbs of flood hydrographs and /or for different seasons on the year.

a. Wash load. Wash load is determined by its supply from upstream sources and is relatively independent of flow discharge, although flow discharge may be a good surrogate parameter because greater runoff from the watershed and greater bank erosion usually accompany higher flow discharge. Wash load is almost always greater on the rising limb of a flood hydrograph when finer sediment stored in the system is re-suspended, as shown in Figure 8-4. Typically, considerable scatter occurs about the average sediment-discharge curve for wash load.

b. Bed-material load. Bed-material load is very dependent on the hydraulic variables, which in turn are closely related to flow discharge; therefore, less scatter about the average sediment-discharge curve is expected. This is another reason to develop separate sediment-discharge curves for wash load and bed-material load.

*

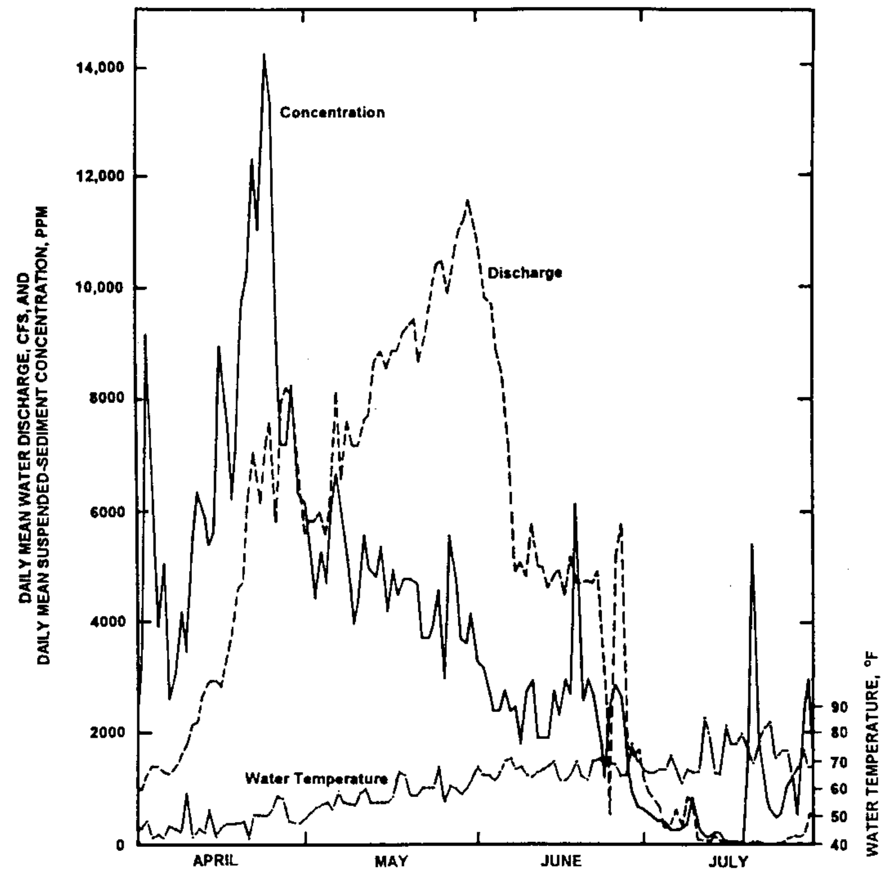

Figure 8-4. Mean daily water discharge and mean suspended-sediment concentration (Nordin and Beverage 1965)

*

8-19. Predicting Future Conditions

The sediment-discharge rating curve may vary with time. This can be due to changes in land use or land management methods, construction of upstream reservoirs that trap sediment, construction of channel stabilization works that decrease bank erosion, or channel improvement work that increases channel conveyance and thus sediment transport potential. A significant downward trend in the average annual sediment discharge of the Mississippi River at Tarbert Landing in Mississippi is shown as an example in Figure 8-5. Although difficult to predict, the possibility of changes in the sediment-discharge rating curve over the project life should be considered.

8-20. Extrapolation to Extreme Events

Sediment data are seldom available for extreme events. This is due both to the infrequency of occurrence and the difficulty in obtaining sediment samples at high flows. Therefore, it is usually necessary to extrapolate the sediment-discharge rating curve developed from measured data. Typically, the rate of increase in sediment discharge with water discharge will decrease with an increase in the water discharge, especially for the finer size classes. The decline in rate of increase is more obvious when sediment concentration is plotted against discharge as shown in Figure 8-6. The decline in rate of increase occurs in the sand sizes as well, as shown in Figure 8-7. A more reliable extrapolation of the measured data for extreme events can be made if the extrapolation is based only on the high flow measured data. In the absence of measured data at high discharges, extrapolation of the sediment-discharge rating curve can be accomplished by calculating a sediment-discharge rating curve for each size class in the bed-material load and using the shape of the calculated curve to approximate the shape of the extrapolated curve.
*

*

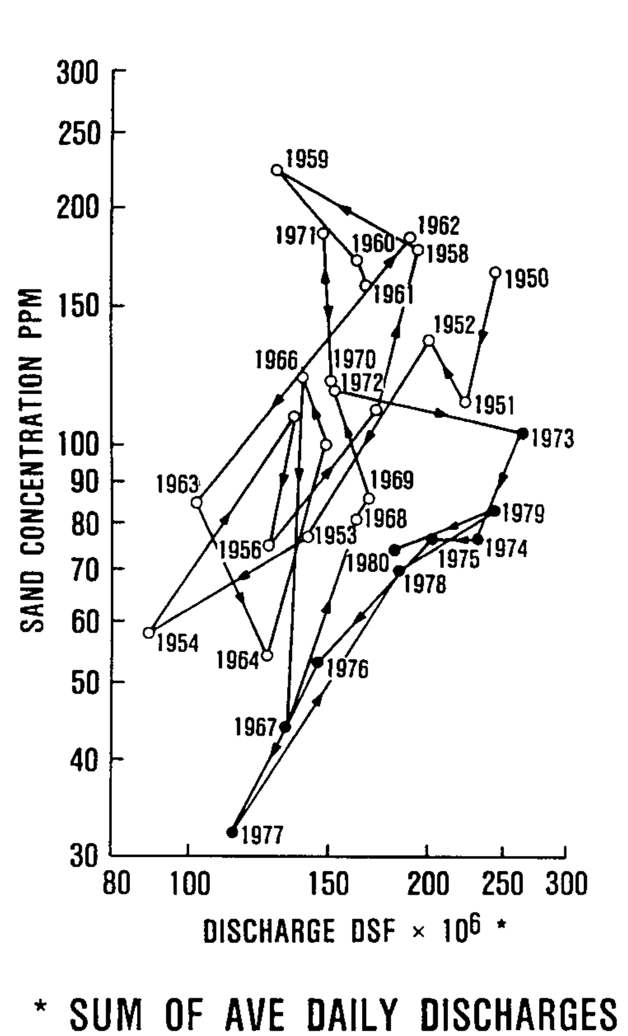

Figure 8-5. Average annual sediment concentration

Expect a high degree of uncertainty for any given grain size that comprises less than 10 percent of the bed.

Section V
References for Chapter 8

American Society of Civil Engineers (ASCE). 1975. "**Sedimentation Engineering**," Manuals and reports on Engineering Practice No. 54, Vito Vanoni, ed., New York.

American Society for Testing and Materials (ASTM). (Published annually.) "Standard Guide for Sampling Fluvial Sediment in Motion," **Annual Book of Standards,** Section 11, Water and Environmental Technology, Vol 11.02, Designation: D 4411-84.

American Society for Testing and Materials (ASTM). (Published annually.) "Standard Guide for Selection of Methods of Particle Size Analysis of Fluvial Sediments (Manual Methods)," **Annual Book of Standards,** Section 11, Water and Environmental Technology, Vol 11.02, Designation: D 4822-88.

American Society for Testing and Materials (ASTM). (Published annually.) "Standard Guide for Core Sampling Submerged, Unconsolidated Sediments," **Annual Book of Standards,** Section 11, Water and Environmental Technology, Vol 11.02, Designation: D 4823-88.

Andrews, E. D., and Parker, G. 1987. "Formation of a Coarse Surface Layer as the Response to Gravel Mobility," **Sediment Transport in Gravel-bed Rivers**, C. R. Thorne, J. C. Bathurst, and R. D. Hey, ed., Wiley and Sons, Chichester, Great Britain, pp 269-325.

Edwards, T. K., and Glysson, G. D. 1988. "Field Methods for Measurement of Fluvial Sediment," U.S. Geological Survey Open-File Report 86-531, Reston, VA.

Einstein, H. A. 1950. "The Bed-Load Function for Sediment Transportation in Open Channel Flows," Technical Bulletin No. 1026, U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.

Guy, H. P. 1969. "Laboratory Theory and Methods for Sediment Analysis," U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5 Chapter C1.

Guy, H. P., and Norman, V. W. 1982. "Field Methods for Measurement of Fluvial Sediment, U.S. Geological Survey Techniques of Water-Resources Investigations Book 3 Chapter C2, Applications of Hydraulics."

Hall, B. R., and Fagerburg, T. L. 1991. "Measurement of Hydrodynamics and Sediment Transport of the Mississippi River at Old River," *Hydraulic Engineering*, Proceedings, 1991 National Conference of the Hydraulics Division, ASCE, Richard Shane, ed., pp 847-852.

Kuhnle, R.A. 1989. "Bed-Surface Size Changes in Gravel-Bed Channel," ***Journal of Hydraulic Engineering***, Vol 115. No 6., pp 731-743.

*

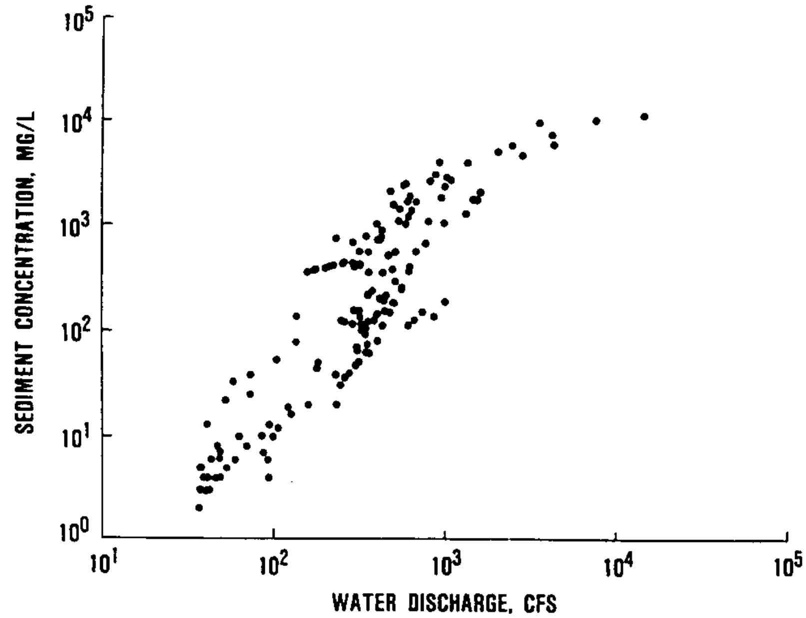

Figure 8-6. Average daily sediment concentration

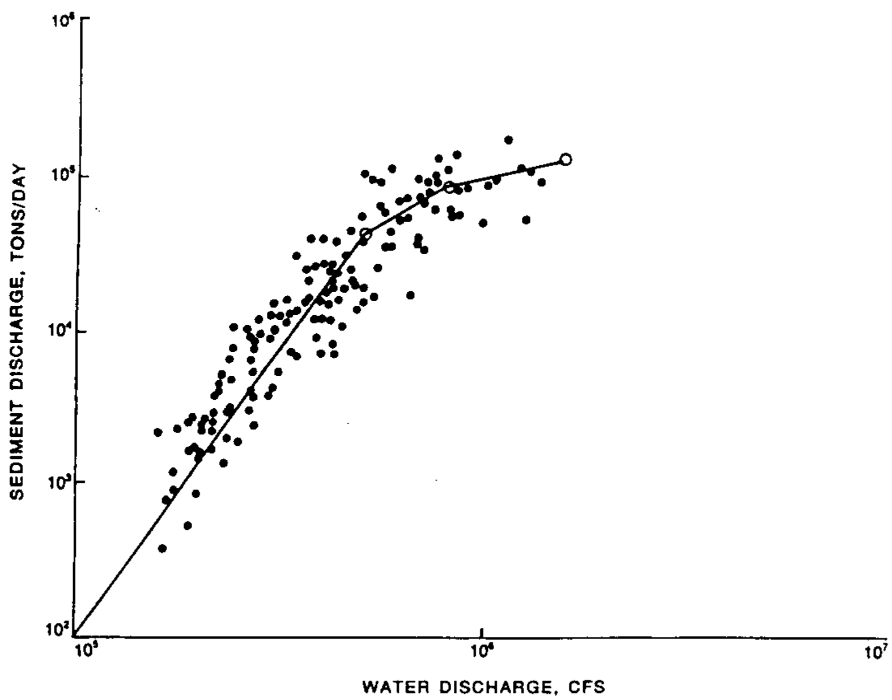

Figure 8-7. Very-fine sand sediment transport

* McGee, R. G., Ballard R. F., and Caulfield, D. D. 1995. "A Technique to Assess the Characteristics of Bottom and Sub-bottom Marine Sediments," Technical Report DRP-95-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nelson, M. E., and Benedict, Paul C. 1951. "Measurement and Analysis of Suspended Sediment Loads in Streams," **Transactions, ASCE**, Vol 116, Paper No. 2450, pp 891-918.

Nordin, C. F. Jr., and Beverage, J. P. 1965. "Sediment Transport in the Rio Grande, New Mexico," Geological Survey Professional Paper 462-F, U.S. Government Printing Office, Washington, DC.

Thomas, W. A., Copeland, R. R., Raphelt, N. K., and McComas, D. N. 1994. "Hydraulic Design Package for Channels - SAM," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Engineer Headquarters (USAEHQ). 1970. "Laboratory Soils Testing," EM 1110-2-1906, Office of the Chief of Engineers, Washington, DC, Change 2, 20 Aug 1986.

U.S. Army Engineer Headquarters (USAEHQ). 1991. "Tidal Hydraulics," EM 1110-2-1607, Office of the Chief of Engineers, Washington, DC.

U.S. Army Engineer Waterways Experiment Station (USAEWES). Conversationally Oriented Real-Time Program System (CORPS) Computer Programs. Available from ATTN: CEWES-IM-MI-C, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

U.S. Interagency Report. 1941. "Methods of Analyzing Sediment Samples," Report No. 4, St. Anthony Falls Hydraulics Laboratory, University of Minnesota, Minneapolis.

Wilcox, P. R., and McArdell, B. W. 1993. "Surface-Based Fractional Transport Rates: Mobilization Thresholds and Partial Transport of a Sand-Gravel Sediment, Water Resources Research, Vol 29., No. 4, pp 1297-1312.

Wolman, M. G. 1954. "A Method of Sampling Coarse River-Bed Material," **Transactions, American Geophysical Union,** Vol 35, No. 6, pp 951-956. *